ANALYSIS OF STABILIZED ADOBE IN RURAL EAST AFRICA

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ABSTRACT

ANALYSIS OF STABILIZED ADOBE IN RURAL EAST AFRICA

Grace Ying Yu Chen

This project seeks to assist people in rural East Africa by proposing sustainable building methods which implement affordable and durable adobe bricks for construction. Adobe, one of the oldest sustainable building materials in the world, is strong when dry but lacks structural integrity when exposed to moisture. Chemical additives such as cement and lime are added into the adobe mix to protect the brick against moisture decomposition. Once the chemicals are added and the mix is formed into a brick, a stabilized adobe brick is formed.

Cement, a stabilizer, is locally available in East Africa, but is generally unaffordable for families in rural areas. Lime is also locally available and costs about half the price of cement. This project investigates reducing the amount of cement to produce an economical and stabilized brick. The tested brick mixes, measured by volume, were

- 10% cement
- 5% cement
- 5% cement+5% lime
- 7% lime with sand
- 7% lime with clay only
- 10% lime with sand

After testing these bricks by water jet, submersion, modulus of rupture, and compression, the 5% cement+5% lime mix and the 7% lime with clay mix proved to be viable options for economical and durable bricks.

The second half of this project contains summaries of research related to stabilized adobe and other soil building methods. A literature search shows that lime mixed with soil containing small particles rich in calcium carbonate and quartz produces proper cementation in the mix called carbonation.

Keywords: Sustainability, East Africa, durability, cement, lime, stabilized adobe brick

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1.0 PURPOSE

This project investigates cement and lime as **stabilizers**[1] to clay adobe using brick mixes commonly used in Itigi, Tanzania. Stabilizers are defined to be chemical agents, such as cement and lime, which increase the durability and strength of adobe. Although cement and lime are industrial chemical additives not native to rural East Africa, they are locally available for purchase.

East African communities currently use cement stabilized bricks for construction if they can afford to purchase cement. People in rural areas have limited finances and are in need of durable bricks. This research serves to assist people in rural East Africa by decreasing the cement content yet maintaining durability in stabilized adobe bricks.

This thesis defines **sustainability** as using locally available and cost effective resources; while cement is an available resource, obtaining cement may not be affordable, which is why finding a minimum quantity of cement to stabilize adobe bricks is important. This thesis also defines sustainability as environmental stewardship, social betterment, and economic growth. Development of the construction industry provides jobs for the native people, so development leads to economic growth.

Rural East Africa's work force consists mainly of hard-working, unskilled laborers. Using sustainable construction methods adoptable by average laborers is important because sustainability promotes long-term development. Once laborers have

[1] Bolded words are defined in the glossary

adopted construction methods, they can continue sustainable design after instructors from developed countries have left.

This thesis also presents a literature review regarding adobe, rammed earth, and soil building methods from around the world. Rammed earth and other soil building research is relevant to the stabilized adobe investigation of this thesis because all methods require structural integrity of soil.

A literature search has shown that **stabilized adobe** research is abundant, but this research is sporadic and not yet compiled. References to relevant articles are also listed in the literature review. The literature review is organized into these categories: cement literature, lime literature, literature of other adobe stabilizing agents, additional stabilized adobe sources, adobe literature, and rammed earth.

2.0 BACKGROUND

The background is divided into three sections: 1) traditional adobe, 2) locations and climates, and 3) advantages of stabilized adobe in rural East Africa. The traditional adobe section discusses the advantages and uses of adobe throughout history; the locations and climates section compares the weather conditions of Itigi, Tanzania, and San Luis Obispo, California; and the advantages of stabilized adobe are discussed in section 2.3.

2.1 Traditional adobe

Natural or traditional adobe, made of soil and water in its simplest form, is an inexpensive building material, and its usage can be traced back to 8000 BC; adobe construction has been found in the Americas, Africa, Europe, Asia, and Australia (Blondet 2003). Although adobe is an ancient building material, it is still used today because construction does not require skilled laborers to build effective buildings. Along with its relatively simple construction techniques, soil is sustainable, recyclable, and abundantly available for brick construction.

Traditional adobe is strong when dry but weak when exposed to moisture. Adobe's vulnerability to moisture poses decomposition problems in areas where torrents of rain and flooding are common. One way to strengthen adobe's resistance against moisture and maintain the sustainable aspects of adobe building is to add a quantity of cement and sand in stabilized adobe.

2.2 Locations and climates

Itigi, Tanzania is located in rural East Africa on the Maasai Steppe Plateau, in the Singida region and in the Mayoni District (Yindi 2008). Figure A below shows Itigi's location relative to surrounding countries and water landmarks.

Figure A: Location map of Itigi, Tanzania and surrounding countries
Source: http://maps.google.com.

Itigi, classified as a plateau climate, is an arid to semi-arid region and experiences an average annual high temperature of 81° Fahrenheit, low temperature of 59° Fahrenheit, has an annual rainfall of 27.4 inches, and is dry from May through October, as show in Table A on the next page (WeatherBonk 2009).

Table A: Monthly weather averages for Itigi, Tanzania
Source: www.weatherbonk.com

Monthly Temperature and Precipitation 30-Year Averages for Itigi, Tanzania			
Month	**High (°F)**	**Low (°F)**	**Precipitation (inches)**
Jan	81	61	5.3
Feb	81	61	5.3
Mar	81	61	4.8
Apr	80	61	3.2
May	80	58	0.0
Jun	79	54	0.0
Jul	79	54	0.0
Aug	81	56	0.0
Sep	84	59	0.0
Oct	86	61	0.0
Nov	84	62	2.8
Dec	81	62	6.0
			Total = 27.4

Itigi and San Luis Obispo have comparable weather conditions. San Luis Obispo, California is located in a Mediterranean climate, which has temperate conditions similar to plateau climates. More specifically, San Luis Obispo experiences an average high temperature of 73° Fahrenheit, low temperature of 48° Fahrenheit, has an average annual rainfall of 24.4 inches, and is dry during June, July, and August, as shown in Table B on the next page (The Weather Channel 2009). Figure B on the next page shows San Luis Obispo's location relative to surrounding states and water landmarks.

Table B: Monthly weather averages for San Luis Obispo, CA
Source: www.weather.com

Monthly Temperature and Precipitation 30-Year Averages for San Luis Obispo, CA			
Month	**High (°F)**	**Low (°F)**	**Precipitation (inches)**
Jan	65	42	5.3
Feb	66	44	5.4
Mar	67	45	4.5
Apr	71	45	1.3
May	73	48	0.5
Jun	78	51	0.1
Jul	80	53	0.0
Aug	82	53	0.1
Sep	82	53	0.4
Oct	79	50	1.0
Nov	72	46	2.2
Dec	66	42	3.6
			Total = 24.4

Figure B: Location of San Luis Obispo, California
Source: www.lib.utexas.edu/maps

San Luis Obispo and Itigi have similar weather characteristics, so brick curing conditions in San Luis Obispo adequately represent curing conditions in Itigi. Also, unskilled laborers produced the adobe bricks in this project, so the brick construction, curing conditions, testing methods, and testing results in San Luis Obispo could be simulated in Itigi.

2.3 Advantages of stabilized adobe in rural East Africa

Villagers in rural East Africa mix clay, water, and sometimes straw to make natural adobe bricks. The clay, water, and straw mixture is pressed in wooden forms and allowed to dry for at least 15 minutes. Then these bricks are placed to form a wall using the same mix as mortar between the bricks. Once the wall is built and dry, the same clay, water, and straw mix is plastered on the wall for moisture protection and for aesthetics.

When villagers have raised enough money, they purchase and install a metal roof to further protect the adobe construction from rain; the metal roof prevents direct rain impact on the adobe walls. The roof also prevents water from entering the interior of the building. However, if rain comes before the metal roof is installed, the rain causes significant damage to the exposed adobe walls. Thatched roofs could also be used to protect adobe from rain. However, abundance of rain could allow water to penetrate through the thatched roof or add excessive weight and cause roof collapse. Using stabilized adobe walls is especially advantageous if the metal roof is not yet installed because stabilized adobe is far more durable than natural adobe.

Cement and lime are available additives to the natural adobe mix used to protect construction from moisture damage, especially before a metal roof is installed. Table C below lists the approximate cost of building materials in Tanzania as of March 2008 (Yindi 2008) compared to the cost in California (www.homedepot.com).

Table C: Approximate cost of building materials in Tanzania and California

Approximate Cost of Building Materials in Tanzania and California (March 2008)		
Item	**Cost in Tanzania**	**Cost in California**
1 cu. foot of cement (yields 48 bricks)	$15.00	$3.30
1 cu. foot of hydrated Lime (yields 48 bricks)	$8.00	$4.10
1 Corrugated Iron Sheet (10 x 2 ft, 10 gauge)	$14.00	$12.50

The minimum wage for workers in Tanzania was implemented on January 3, 2008 at 35,000 shillings ($27.56 US dollars as of November 2008) per month in rural areas. According to *The Africa Guide* (2008), the average monthly cost of living in Tanzania for a family of four is $58 US. Family members working at minimum wage generally struggle to pay for the average cost of living. Given the average wages of families in rural East Africa, the construction materials listed in Table C above are unaffordable.

Also, budgeting construction expenses is not common in rural East Africa (Mwangi 2008). Villagers purchase materials as they can afford them, so when funds run out, construction ceases. The cost of cement increased over 50% during 2007 due to increased fuel prices (Aron 2008). The inability to pay for materials as construction progresses due to increased cost of materials is often the reason for unfinished structures.

With minimal income and cost increase of materials, completing structures within a year in rural East Africa is rare (Kamndaya 2008).

Since builders in rural East Africa traditionally purchase materials as they build, moisture-resistant adobe is a favorable construction material to use. Structures made with stabilized adobe would survive multiple seasons of rain until villages have raised enough money to purchase a metal roof.

3.0 EXPERIMENTATION

This chapter is divided into seven sections: 1) adobe brick mix and test introduction, 2) adobe brick production, 3) water jet test, 4) submersion test, 5) modulus of rupture test, 6) compression test, and 7) conclusions. The following section describes the adobe brick mixes and tests conducted in this project.

3.1 Adobe brick mix and test introduction

Adobe bricks for this project were made with soil native to San Luis Obispo, California. The adobe mixes and tests are listed in

Table D and Table E on the next page. The 100% clay adobe mix, traditionally used in rural East Africa, is weak when exposed to moisture. The 10% cement mix, measured by volume, recommended by Micek et al., has proven to be a strong and durable brick. However, adding 10% cement in a brick is likely to be unaffordable for rural East Africans. This thesis sought to decrease the amount of cement added into each adobe brick while maintaining durability.

Pastor Williams Yindi of Itigi, Tanzania is currently constructing a sanctuary with 5% cement+5% lime stabilized adobe, measured by volume. This project investigates the strength and durability of his bricks. Finally, the Chemical Lime Company investigated varying proportions of lime in stabilizing adobe and recommended the 7% lime mix, measured by volume. However, they used highly technical construction methods in laboratory conditions, so this project investigates the durability of 7% lime stabilized adobe made with unskilled laborers using unsophisticated technology.

Table D: Adobe brick mixes made and tested in this thesis

Adobe Brick Mixes (%, measured by volume)						
		Clay	Sand	Cement	Lime	**Reference**
Baseline Mixes	100% Clay	100	0	0	0	
	10% Cement	30	60	10	0	Micek et al., 2006
Variable Mixes	5% Cement+ 5% Lime	30	60	5	5	Itigi, Tanzania mix
	5% Cement	30	65	5	0	
	7% Lime with Sand	30	63	0	7	
	7% Lime with Clay	93	0	0	7	Chemical Lime Company, 2008
	10% Lime	30	60	0	10	

Table E: Durability and strength tests performed on stabilized adobe bricks

Durability and Strength Tests Performed on Stabilized Adobe Bricks		
		Reference
Durability Tests	Water Jet	Micek et al. 2006
	Submersion	Micek et al. 2006
Strength Tests	Modulus of Rupture	ASTM C99-87
	Compression	ASTM C170

To simulate the unskilled labor force in rural East Africa, students with different backgrounds and unfamiliar with brick-making were used. Some of these students were in high school; others attended Cal Poly and majored in architecture, architectural engineering, construction management, landscape architecture, civil engineering, or electrical engineering.

The manager of the brick production demonstrated to the workers how to mix the clay, sand, cement, lime, and water. The manager then supervised the brick production. This method of demonstration and supervision reflects the work environment in rural East Africa. Simulating rural East African brick production in San Luis Obispo is important for the stabilized adobe brick characteristics to be similar in both areas.

The tools used for making adobe bricks in San Luis Obispo, which are also obtainable in rural East Africa, were pick-axes, shovels, rocks for pounding, window screens used as a wire mesh for sifting, trays for mixing, and manual brick presses.

3.2 Adobe brick production

Brick production began with obtaining soil samples. Soil from Poly Canyon, which is made of geological formations of serpentinite, taken by the Brizziolari Creek on Cal Poly, San Luis Obispo property was used for the soil stratification test (Holland and Keil 2009). The native soil surface was hard, so only four inches of the top layer was collected to fill four transparent glass jars. Each jar had a constant diameter.

After placing soil samples into jars, the jars were filled with water until the water surface was higher than the soil surface. The jar lids were tightly replaced, and then the jars were shaken. Finally, the jars were placed on a shelf for a day for the soil to settle. Once settled, the different soil size particles stratified. The thickness of each soil layer was measured and recorded. Figure C on the next page displays an example of how the soil stratification test could result. Figure D and Table F on page 14 display the Poly Canyon soil stratification results. Using the soil stratification test, the proportion of clay, sand, or aggregate could be calculated with respect to the whole. The soil distribution of Poly Canyon soil is listed in Table G on page 15. According to the soil stratification test, the native soil in Poly Canyon consists primarily of clay.

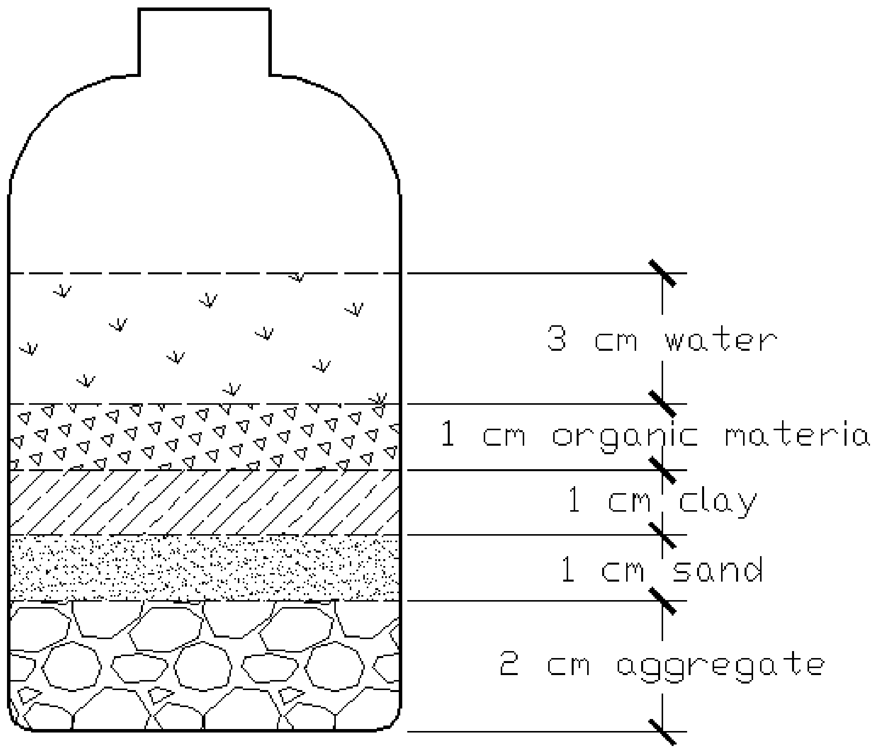

Figure C: Example of soil stratification test results
Source of soil stratification test procedures: Micek et al. (2006)

Figure D: Poly Canyon soil stratification test showing clay soil, water, and organic material

Table F: Poly Canyon soil stratification results

Poly Canyon Soil Stratification (height cm)				
	Jar 1	Jar 2	Jar 3	Jar 4
Water	2.0	0.5	2.0	2.5
Organic Material	0.5	0.5	0.5	0.5
Clay	12.0	11.0	11.5	11.0
Sand	0.0	0.0	0.0	0.0
Aggregate	0.0	0.0	0.0	0.0

Table G: Average Poly Canyon soil stratification distribution

Average Poly Canyon Soil Distribution, (%)	
Organic Material	4
Clay	96
Sand	0
Aggregate	0

Workers pounded Poly Canyon soil with stones to break the dirt clots, as shown in Figure E below. After the soil was broken down to fine particles, it was sifted over a window screen. For simplicity and convenience, the particles passing through the window screen were considered clay. The clay that passed through the screen was collected for brick-making, as shown in Figure F on the next page. The pounding and sifting is by far the most time-consuming segment of the brick-making process.

Figure E: Workers pound dirt clots with stones to make finer soil particles

Figure F: Fine soil particles sifted through a window screen

The amount of material used for each brick was measured by volume using a water pitcher with notches, as shown in Figure G below, that designate the proportions (Table H on the next page) needed for the different adobe brick mixes. Each pitcher had ten notches.

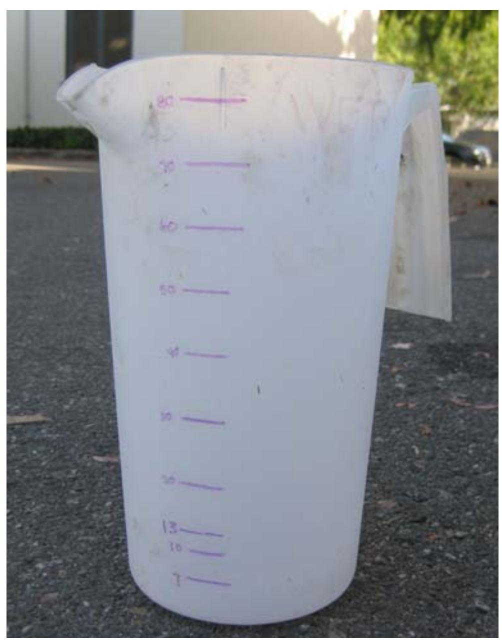

Figure G: Pitcher with notches for measuring mix proportions by volume

Table H: Proportion of materials for each brick

Proportions of Materials used in Each Brick (Units in notches, with ten notches to a pitcher)				
Mixes	Clay	Sand	Cement	Lime
Clay	2 pitchers	0	0	0
10% Cement	6	12	2	0
5% Cement	6	13	1	0
5% Cement, 5% Lime	6	12	1	1
7% Lime, sand	6	12.5	0	1.5
7% Lime, clay only	18.5	0	0	1.5
10% Lime, sand	6	12	0	2

The optimum water content in the mix was determined by rolling the mix into a glossy ball between the hands, as shown in Figure H on the next page. If the ball, when dropped from three feet from a surface, formed a pyramidal shape upon contact with the surface, then the mix had the proper amount of moisture (Godbey and Thomson 2009). Figure I on the next page shows an example of a pyramidal shape. After thorough mixing by hand, the mix was placed in a manual ram (Figure J on the next page) and pressed to form a 3x6x12-inch brick.

Figure H: Optimal water content determined with glossy ball

Figure I: Brick mix's pyramidal shape showed optimal water content

Figure J: Manual press used to make each adobe brick

The bricks in this project were compressed using a manual ram, which is a technique different from the traditional method of making adobe. Adobe is traditionally placed in molds and cured in direct sunlight, which is around 80°F. However, curing stabilized adobe in direct sunlight is not appropriate because the heat resulting from direct sunlight causes the cement to flash-set. A stabilized brick has flash-set when the surface of the brick has quickly hardened thus preventing the interior of the brick to continually absorb oxygen (American Concrete Institute 2009). Oxygen absorption is important for the curing process. Flash-setting in bricks causes weak, unconsolidated, and unusable bricks.

Cement, which cures by a slow process called hydrolysis, binds the sand and clay particles together. Because hydrolysis is a slow process, cement stabilized bricks should cure in cool environments. Compressing the aggregate with the cement allows for proper adhesion and unification for each brick. Cement stabilized should be compressed and cured in the shade for optimal consolidation.

In rural East Africa, the bricks were traditionally cured in the sun. The bricks in this thesis cured in the shade, as shown in Figure K on the next page, for at least 28 days where they were lightly sprayed with water every three days. Moistening the bricks cools down the bricks and slows down the hydrolysis process, which allows optimal consolidation throughout the brick. Because the bricks were vulnerable to rain during their curing stage, they were covered with a waterproof tarp.

Figure K: Stabilized adobe bricks curing in the shade

3.3 Water jet test

The water jet test indicated the durability of the bricks when subject to heavy rain conditions. The water jet test was chosen because the water pressure exerted on the bricks could be calculated and kept constant. Limiting variability in the water jet test results in consistent brick performance.

The thickness of each adobe specimen was measured, and then the water pressure exerted on the bricks was calculated, as described in section 3.3.1. The constant water pressure was exerted at the center of the bricks for 30 seconds, and then the depth of penetration was measured. Finally, the percent of penetration was calculated.

3.3.1 Water pressure derivation

Fluid dynamics was used to calculate the pressure of the water jet. The following derivation is taken from "Introduction to Fluid Mechanics, 6th Edition," by Robert W. Fox, Alan T. McDonald, and Philip J. Pritchard. Equation 1 on the next page uses the conservation of mass of water to calculate the water velocity. Equation 2 below uses the conservation of momentum of the water to calculate the force of the exiting water. Figure L below describes the conservation of mass through a nozzle. The conservation of mass equation of water is the following:

$$0=\int(\rho V_1\, dA_1)+\int(\rho V_2\, dA_2) \qquad \text{(Equation 1)}$$

Where, ρ is the density of water (62.4 lbs/ft^3),
V_1 is the velocity vector of water entering the nozzle,
V_2 is the velocity vector of water exiting the nozzle,
A_1 is the cross-sectional area vector of the hose, arrow pointing normal to the surface
A_2 is the cross-sectional area vector of the nozzle, arrow pointing normal to the surface.

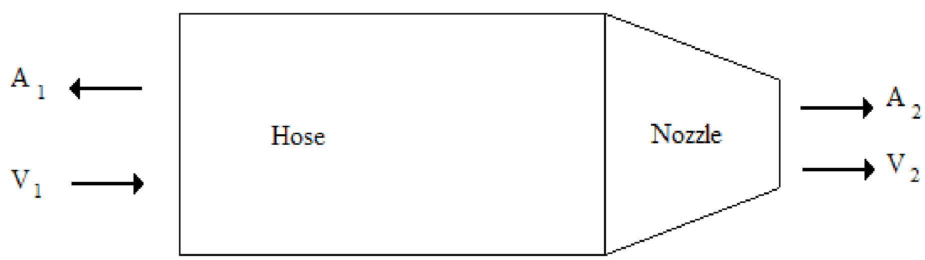

Figure L: Conservation of mass of water

The density of water is unchanged, so Equation 1 can be simplified to the form:

$$-V_1A_1 = V_2A_2 \qquad \text{(Equation 1.1)}$$

Equation 2 is the conservation of momentum, shown below:

$$F=\int(\rho V_1)(V_1 dA_1)+\int(\rho V_2)(V_2 dA_2) \qquad \text{(Equation 2)}$$

Where, F is force exerted,
ρ is the density of water (62.4 lbs/ft^3),
V_1 is the velocity vector of water entering the nozzle,
V_2 is the velocity vector of water exiting the nozzle,
A_1 is the cross-sectional area vector of the hose,
A_2 is the cross-sectional area vector of the nozzle,

Equation 2 can be reduced to the following form:

$$F=\rho(V_2^2A_2 - V_1^2A_1) \quad \text{(Equation 2.1)}$$

Equation 2.1 is used to calculate the force of the water jet stream.

Finally, the water pressure can be calculated using Equation 3:

$$P=F/A_2 \quad \text{(Equation 3)}$$

Where, P is the pressure,
F is the force found by Equation 2.1,
A_2 is the area of the nozzle.

3.3.2 Water jet materials and procedures

The materials needed for this test are the following:

- Garden hose
- Nozzle
- Ruler
- Stand for bricks

The thickness of the adobe bricks were measured, as shown in Figure M below, and the bricks were placed on a stand, as shown in Figure N on the next page.

Figure M: Thickness of the brick measured for the water jet test

Figure N: Bricks on a stand for the water jet test

The water pressure from the nozzle was calculated and constant water pressure was exerted at the center of each brick for 30 seconds, as shown in Figure O below. The penetration depth was measured (Figure P on the next page) and the percent of penetration was calculated.

Figure O: Water at constant pressure exerted on brick for 30 seconds

Figure P: Measured depth of water penetration after testing

3.3.3 Water jet results and discussion

The percentage of water penetration for each type of brick is listed in Table I below.

Table I: Average water penetration

Water Jet Test Results After 30 Second Water Exertion	
Type of Brick	**Average Penetration (%)**
Adobe	0.0
10% Cement	0.0
5% Cement	11.3
5% Cement+5% Lime	0.0
7% Lime, Sand	42.7
7% Lime, Clay only	1.68
10% Lime, Sand	27.0

Penetration depth of 0% was this investigation's standard for a sufficiently durable brick. The approximate rate of water penetration was also visually noted. As soon as the water breached the surface of the brick, the penetration rate increased. For this reason, the 0% water penetration standard was chosen for brick durability. If some level of penetration were acceptable, the entire brick would likely deteriorate after the first rainy season.

Results for the clay adobe bricks could not be accurately determined; the dimensions could not be measured because the bricks cracked into three to four pieces during curing. Although the bricks were broken, they still underwent the water jet test. Surprisingly, the clay adobe bricks did not have any depth of penetration. Instead, the adobe surface slid off with the water.

The 10% cement bricks performed well, as expected, for those bricks did not have any visible penetration depth. The 5% cement brick (shown in Figure Q on the next page) had 11.3% penetration depth, so this mix does not provide sufficient durability.
The 5% cement+5% lime bricks meet durability standards, for the constant water pressure did not penetrate the brick surface.

The lime with sand bricks had deep penetration depths, so these mixes are not acceptable. The 7% lime with clay bricks (Figure R on the next page) performed much better than the lime with sand bricks. However, the 7% limes with clay bricks do not meet the 0% penetration standard set in this thesis.

Figure Q: 5% cement stabilized brick with 11.3% water penetration depth

Figure R: Lime stabilized clay brick with 1.68% water penetration depth

3.4 Submersion test

The submersion test indicates the durability of the bricks when exposed to flooding. Flooding is a rising or overflowing of a body of water over normally dry land, and could occur after sustained heavy rainfall or rapid snow melt. Flooding could be a problem in areas near to bodies of water. This thesis used Itigi, Tanzania as a design example, where flooding is not a common problem.

First, the criteria for damage evaluation were determined: Negligible, Light, Moderate, and Severe. The descriptions of these ratings are listed:

Negligible: the brick does not exhibit any visible damage. No indentations occur with the pressure of one finger.

Light: the brick does not exhibit any visible damage, but indentations occur with slight pressure.

Moderate: the brick shows visible deterioration and indents with slight pressure. The water remaining in the container is brown due to brick decomposition.

Severe: the brick loses most of its surfaces or edges. The water is brown and muddy from erosion, and the brick cannot withstand any pressure.

Five-gallon buckets of water were filled with potable water (Figure S on the next page), the same bricks tested in water jet were gently placed in the buckets (Figure T on the next page), and the bricks were submerged for 24 hours (Figure U on the next page). The bricks' deterioration was evaluated after one hour and after 24 hours, as prescribed by Micek et al. (2006).

Figure S: Buckets filled with potable water for submersion test

Figure T: Two bricks gently placed in each bucket of water

Figure U: Bricks submerged in water

The average rating after 1-hour submersion and 24-hour submersion is listed in Table J below.

Table J: Average rating for bricks after 1-hour and 24-hour submersion

Submersion Test Results		
Brick Type	**1 Hour**	**24 Hours**
Clay Adobe	Severe	Severe
10% Cement	Negligible	Negligible
5% Cement	Light	Light
5% Cement+5% Lime	Negligible	Negligible
7% Lime, Sand	Moderate	Severe
7% Lime, Clay only	Moderate	Severe
10% Lime, Sand	Light	Severe

Three people individually rated each brick and compared ratings after all the bricks were observed. If any two people differed in rating a brick, the brick was reconsidered until a consensus was attained.

The standard for this submersion test was having no visible damage after 24 hours of flooding. Clay adobe bricks are vulnerable to moisture. As expected, the clay adobe bricks (Figure V on the next page) did not survive an hour in water submersion; the clay adobe bricks dissolved into mud. Also as expected, the 10% cement bricks (Figure W on the next page) performed extremely well in water submersion. None of the 10% cement bricks had any visible damage. The 5% cement bricks (Figure X on page 31) performed relatively well, with only slight damage after 24 hours of water submersion.

The 5% cement+5% lime bricks (Figure Y on page 31) also performed well with no visible damage. The 7% lime bricks with sand (Figure Z on page 32), the 10% lime bricks (Figure AA on page 32), and the 7% lime with clay only bricks had severe damage after 24 hours of water submersion. Only the 10% cement mix and the 5% cement+5% lime mix meet the performance standard in submersion.

Figure V: Clay adobe after one hour of water submersion

Figure W: No visible damage for 10% cement bricks after 24-hour submersion

Figure X: Weak edges for 5% cement bricks after 24-hour submersion

Figure Y: No visible damage for 5% cement+5% lime bricks after 24-hour submersion

Figure Z: Severe damage for 7% lime bricks after 24-hour submersion

Figure AA: Weak edges for 10% lime bricks after 24-hour submersion

The bricks damaged by the water jet test deteriorated more severely under water submersion; the hard surface of the brick was already breached, which increases vulnerability in the brick. Bricks undergoing a water jet test followed by a submersion test attempted to simulate real life conditions of heavy rain pounding on the bricks followed by flooding. However, the water jet pressure to the center of the brick was likely to cause more severe damage compared to the evenly distributed pressure of rainfall. Also, each tested brick was completely submerged in water, but in real life conditions, flooding is likely to occur on the exterior side of the wall. The submersion test was also a more severe reproduction of real life conditions.

3.5 Modulus of rupture test

The intent of the modulus of rupture test was to test and verify that each batch of bricks meet quality standards. The modulus of rupture test could be performed in a laboratory or on site. According to the Masonry Standards Joint Committee (MSJC), the allowable flexural tensile stress, or modulus of rupture, for clay and concrete masonry is 30 psi (MSJC Table 2.2.3.2). Using 30 psi as the quality standard, the allowable rupture load could be determined. Quality control could be applied on site using the calculated allowable rupture load, assuming that the dimensions of the bricks are consistent.

On site, the modulus of rupture test would be set up as shown in Figure BB on the next page. A person, weighing as much as the allowable rupture load, stands on the rod across the center of the brick. If the brick withstands the person's weight, that brick meets quality standards for flexural tensile strength.

For this thesis, the modulus of rupture was determined for each brick using a laboratory testing machine. The test was set up in the testing machine as shown in Figure CC on the next page, and the rupture load was recorded after each test. With the rupture load, the modulus of rupture can be calculated using Equation 4 from the American Society of Testing and Materials (ASTM) C99-87. The average results for each brick type, set up with eight inches between supports, are listed in Table K on page 35.

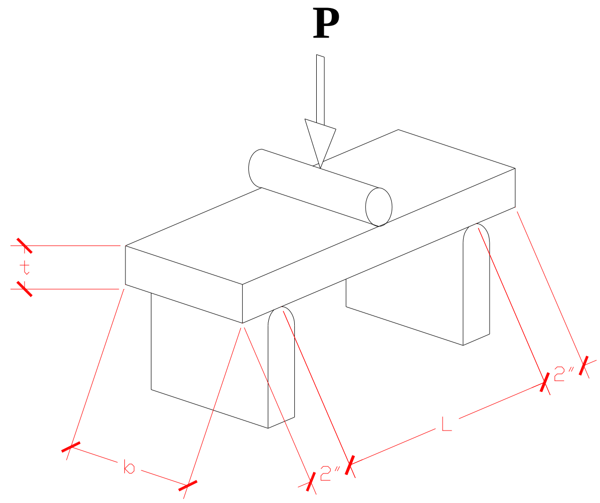

Figure BB: Modulus of rupture test set-up

$$M_r = \frac{3PL}{2bt^2} \qquad \text{(Equation 4)}$$

Where, P = Rupture load
L= Length between supports
b = Width of brick
t = Thickness of brick

Figure CC: Modulus of rupture laboratory testing set-up

Table K: Average modulus of rupture

Modulus of Rupture Results	
Brick Type	**Mr (psi)**
Clay Adobe	Not tested
10% Cement	81.9
5% Cement	17.6
5% Cement+5% Lime	57.4
7% Lime, Sand	2.3
10% Lime, Sand	14.3
7% Lime, Clay only	22.1

ASTM C99-87 specified the thickness of the bricks to be 1.25 inches, but the bricks tested in this analysis averaged three inches. To verify that the bricks will fail in tension instead of shear, the three-inch bricks went through preliminary modulus of rupture tests. A vertical failure crack forming directly beneath the load designates a tensile failure while a diagonal failure crack forming near the supports designates a shear failure. The failure crack of the bricks after preliminary testing was vertical, as shown in Figure DD below, Figure EE, and Figure FF on the next page. Vertical cracking shows that the bricks in this analysis were suitable for modulus of rupture testing.

Figure DD: Modulus of rupture field test with a person's weight as rupture load

Figure EE: Tension failure of a three-inch brick

Figure FF: Vertical failure crack verifying tension failure

The 10% cement and the 5% cement+5% lime mix meet the allowable MSJC modulus of rupture standard of 30 psi, but the remaining mixes do not. The clay adobe bricks broke into pieces during curing and transportation, so they could not be tested for their modulus of rupture.

If a 3x6x12-inch brick, set up on site with eight inches between supports, fails under 135 pounds, it has 30 psi tensile strength. With the modulus of rupture test set up, a

135-pound person on site could stand on each brick to verify that each brick meets quality standards.

3.6 Compression test

The compression test exhibits the capacity of the bricks when subject to an axial load. ASTM C170- 06 specifies testing a cube specimen at least two inches in height with 1:1 ratio of height to lateral dimension. The bricks in this analysis could not be sawed into cubes due to their fragility, so they were sawed to 3x6x6-inch specimen instead. The specimen had an axial load applied parallel to the bedding. The direction of bedding is shown in Figure GG below and the direction of applied load is shown in Figure HH on the next page. Rubber pads were placed on top and beneath each specimen during testing to ensure uniform loading on the bearing areas. The average compressive strengths of the specimen are listed in Table L on the next page.

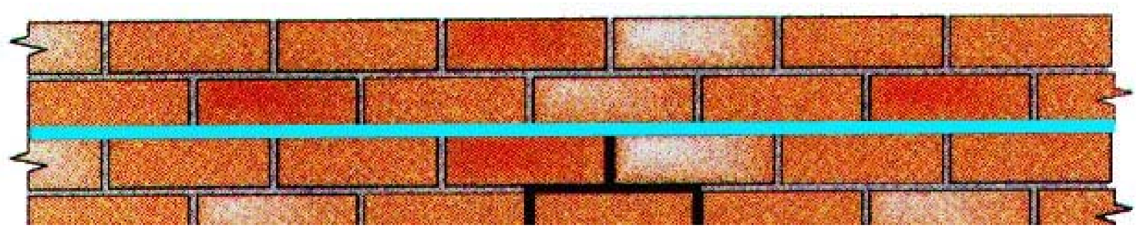

Figure GG: The direction of bedding shown with bold turquoise line
Source: www.rotafix.co.uk

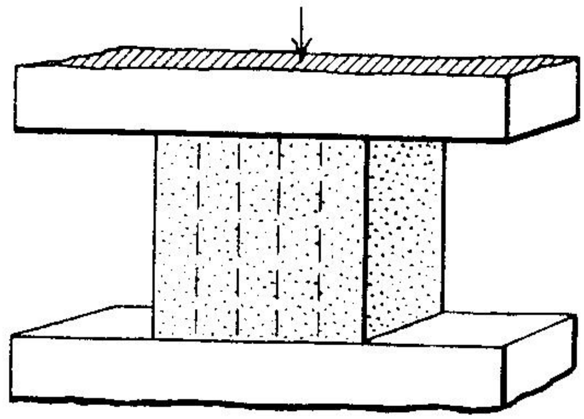

Figure HH: Compression load parallel to bedding. Direction of bedding shown with dashed lines.
Source: ASTM C170-06

Table L: Average compressive strength with load parallel to bedding

Average Compressive Strength, C	
Brick Type	**C (psi)**
Clay Adobe	Not Tested
10% Cement	488.34
5% Cement	55.74
5% Cement, 5% Lime	204.18
7% Lime, Sand	21.93
10% Lime, Sand	33.67
7% Lime, Clay only	118.34

The 10% cement bricks performed far better in compression than all other bricks in this investigation. The 5% cement+5% lime bricks have an acceptable compressive strength, but the remaining bricks do not. The sawing of the bricks is most likely the reason for the reduced compressive strength in the bricks.

Morel, Pkla, and Walker (2007) stated that typical compressed earth blocks (CEB) made with a manual press have compressive strengths in the range of 2-3 MPa (290-435 psi). Only the 10% bricks in this investigation fall into the typical compressive strength category. The 5% cement+5% lime bricks fall just short of the typical range.

3.7 Conclusion

According to the results, lime by itself when mixed with sand is not a viable substitute for cement. Researchers recommend soil particle sizes less than 0.3mm to be mixed with lime (Millogo et al. 2008). In this thesis, at least 60% sand was added in some of the lime mixes; sand contains particle sizes twenty times larger than the recommendation. The addition of sand was decided to be the main cause of the poorly performing lime stabilized bricks.

The 7% lime brick with clay had only 1.68% penetration depth, which shows that lime bricks made with fine particles improved pozzolanic action thus improving durability. Pozzolanic action occurs when chemicals are added to the brick mix to improve durability and strength. Table M on the next page lists the approximate cost and performance results of each brick mix.

Table M: Cost and performance comparison of brick mixes after water jet, submersion, modulus of rupture, and compression test

Adobe Brick Mixes Cost and Performance Comparison (Cost Approx. for Itigi, Tanzania)						
Brick Mixes	**Cost/Brick**	**Jet, %**	**Sub. Damage**	**M_r, psi**	**Comp., psi**	**Pass all tests?**
100% Clay	$0.00	0.0	Severe	Not Tested	Not Tested	No
10% Cement	$0.31	0.0	Negligible	81.9	488.34	Yes
5% Cement+5% Lime	$0.24	0.0	Light	57.4	204.18	No
5% Cement	$0.16	1.68	Negligible	22.1	118.34	No
7% Lime w/ Sand	$0.12	11.3	Severe	17.6	55.74	No
7% Lime w/ Clay	$0.12	27.0	Severe	14.3	33.67	No
10% Lime	$0.17	42.7	Severe	2.3	21.93	No

After performing durability and strength tests on the bricks, results show that only the 10% cement bricks perform at an acceptable level in all tests. However, the 5% cement+5% lime bricks and the 7% lime with clay bricks could be acceptable. Because flooding is not common in Itigi, the 7% lime with clay bricks, which performed well in all tests except water submersion, is recommended for future construction in Itigi. Using 5% cement+5% lime instead of 10% cement decreases the cost of bricks by 23%. Using 7% lime with clay instead of 10% cement decreases the cost of bricks by 61%. The 7% lime with clay mix is the most affordable choice.

To improve the strength and durability of stabilized adobe bricks, organic material in the soil should be minimal. The soil on the surface contains more organic material compared to the soil deeper beneath the surface, so using deeper soil is recommended. If using surface soil is more practical, burn away the organic material by placing the soil in an oven at 150° Fahrenheit (Walker and Stace 1997).

Another way to improve the performance of stabilized adobe is to reduce the amount of clay in the mix. Clay, an absorbent mineral, weakens the bond between the cement and the soil matrix; weak bonds allow pockets of unstabilized soil to form during wet mixing. Research has shown that the blocks improved in compression and durability with increased cement content and clay content less than 20% (Walker and Stace 1997). Because clay is an absorbent material, the 7% lime with clay bricks from this thesis performed poorly in the submersion test.

The chemical composition of clay also plays a role in improving the strength and durability of stabilized adobe. According to Millogo et al. (2008), lime performance is enhanced with quartz-rich clayey soil. The native soil used in the bricks in this thesis lacked quartz, so the bricks performed poorly compared to bricks tested by researchers listed in the literature review.

4.0 LITERATURE REVIEW

Adobe is one of the world's oldest sustainable building materials. Because sustainability has become increasingly popular within the past 30 years, people have extensively researched adobe as a building material. This research is abundant yet sporadic, so a secondary purpose of this thesis is to organize adobe-related research. This literature review contains compiled summaries of existing research. Listed below are the titles of each section in this literature review:

4.1 Cement literature

4.2 Lime literature

4.3 Literature of other adobe stabilizing agents

4.4 Additional stabilized adobe sources

4.5 Adobe literature

4.6 Rammed earth

Section 4.4, Additional stabilized adobe sources, provides a bibliography of articles related to stabilized adobe; these articles were found in a database search but not used in this research. Rammed earth could be considered an advanced form of compressed adobe, so reviews regarding moisture-resistant rammed earth are included in section 4.6.

4.1 Cement literature

Stabilized adobe is made of soil and chemical admixtures which limit water absorption into the adobe and enhance durability. Cement, when combined with water, is a common additive used to bind minerals, such as clay and sand, into a homogeneous solid block. In addition to binding minerals, cement provides durability and strength in building materials. Although cement-stabilized bricks are sufficiently durable and strong, these bricks are generally unaffordable for average families in rural East Africa.

Various studies have been conducted to evaluate different stabilizers. The following sections 4.1.1 through 4.1.3 describe cement stabilized adobe tests and conclusions drawn by researchers listed below:

4.1.1. *Adobe brick design,* by Micek et al. (2006)

4.1.2. *Influence of natural pozzolan, colemanite ore waste, bottom ash, and fly ash on the properties of Portland cement,* by Targon et al. (2003)

4.1.3. *Properties of some cement stabilized compressed earth blocks and mortars*, by Walker and Stace (1997)

These articles are beneficial to this research, so a summary of each article is given.

4.1.1 Adobe brick design

Micek et al. (2006) made adobe bricks with a manual ram, the same ram used for this thesis. They tested three stabilized adobe brick mixes (Table N on the next page) and three **augmented adobe** brick mixes (Table O on the next page). The tests are listed in Table P on the next page. Adobe is considered augmented when natural materials such as straw, rice hulls, or bamboo are added to the mix to reduce cracking and moisture absorption. Results show that organic materials in clay decrease the size and amount of cracking in bricks, but do not provide adequate durability in the bricks. Results also show that only the cement mixes had the durability to withstand water. This senior project revealed the importance of cement in making adobe moisture-resistant. Testing methods, listed below, and results from this senior project were used as a guide for this thesis.

Table N: Stabilized adobe mixes tested by Micek et al. (2006)

Stabilized Adobe Mix Proportions (Measured by volume)				
	Clay	Sand	Cement	Fly-ash
Cement	30%	60%	10%	
Fly-ash	30%	60%		10%
Cement and Fly-ash	30%	60%	5%	5%

Table O: Augmented adobe mixes tested by Micek et al. (2006)

Augmented Adobe Mix Proportions (Measured by volume)					
	Clay	Sand	Rice Hulls	Wet Bamboo	Dry Bamboo
Rice Hulls	90%		10%		
Wet Bamboo	90%			10%	
Dry Bamboo	90%				10%

Table P: Adobe durability and strength tests conducted by Micek et al. (2006)

Adobe Tests Conducted by Micek et al.	
Durability Tests	**Strength Tests**
Water Jet	Compression
Submersion	Modulus of Rupture

The 10% cement mix's ultimate compressive stress averaged 820 psi, and the cement and fly ash mix had the second highest average of 550 psi. All the augmented adobe mixes averaged 200 psi in compressive strength, which does not meet the New Mexico Building Code (NMBC) minimum ultimate compressive strength of 300 psi. The NMBC has the most conservative standard for compressive strength, compared to other codes. Figure II below compares the cement-stabilized brick ultimate values from code standards, Micek et al.'s research, and from this thesis (Chen).

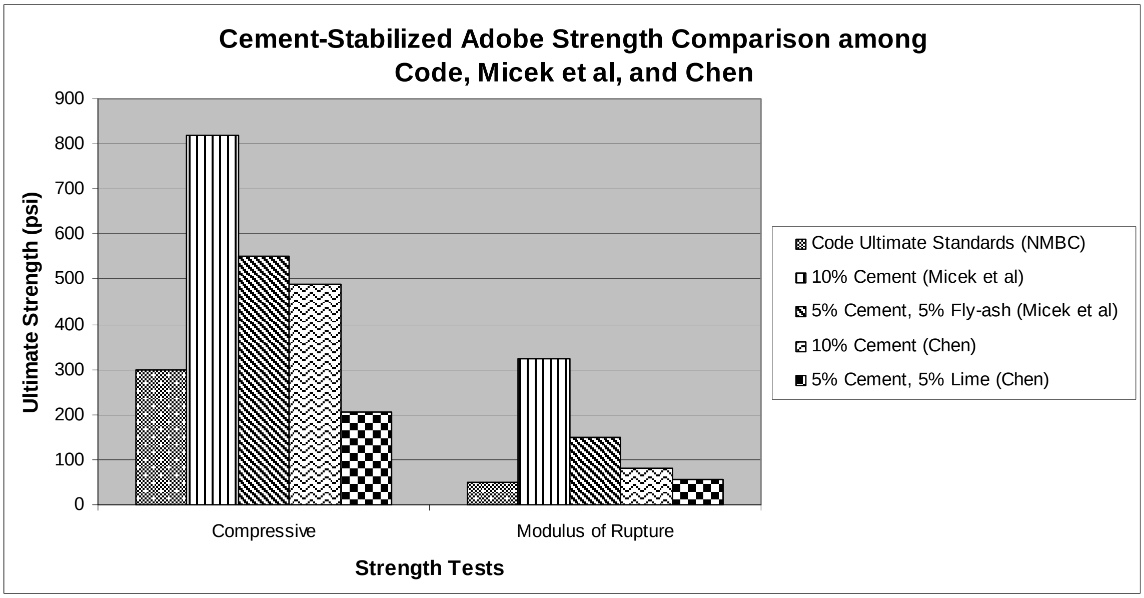

Figure II: Ultimate strength comparison of Code, Micek et al., and Chen

The stabilized adobe bricks made in Micek et al.'s research and in this investigation (Chen's) both meet code standards for the modulus of rupture test, which is 50 ksi (NMBC). As shown in Figure II above, Micek et al.'s bricks had consistently higher modulus of rupture than Chen's bricks; Chen's bricks had only 20% of Micek et al.'s modulus of rupture strength.

Micek et al.'s compression test results had significantly higher compressive strength than Chen's. The NMBC specifies 300 psi for bricks' ultimate compressive strength, which Chen's 5% cement+5% lime bricks do not meet. A reason for such drastic variation in strength results could be because Micek et al. used purchased, pure, clean clay in all their bricks while site soil was used in this thesis. The site soil used in this investigation consisted of 4% organic material, which weakened the bricks. When using site soil for brick-making, soil deeper than 4 inches from the surface should be used.

For the water jet test, Micek et al. applied constant water pressure on each brick for 30 seconds. Micek et al.'s results are consistent with the results from this thesis: the cement stabilized bricks did not have any water penetration and the remaining bricks did.

For the submersion test, which simulates flooding, bricks were submerged in buckets of water for 24 hours. After an hour of submersion, all the augmented bricks dissolved. After 24 hours, the stabilized bricks did not show any signs of degradation. Their submersion test results resembled the results from this thesis.

Micek et al. recommended the 10% cement mix for the bottom 2 feet of wall to resist water absorption when the site has flooded. The rest of the wall should be made with 5% cement+5% fly ash bricks for they are sufficiently durable and are a less expensive alternative to the 10% cement bricks. The 5% cement+5% lime mix tested in this thesis would also be a viable alternative to the more costly 10% cement bricks.

4.1.2 Influence of natural pozzolan, colemanite ore waste, bottom ash, and fly ash on the properties of Portland cement

Targon et al. (2003) investigated natural **pozzolan**, colemanite ore waste, **coal fly ash**, and **coal bottom ash** as supplementary materials in concrete. Since cement is an expensive material in rural East Africa, replacing a portion of cement with natural pozzolan, colemanite ore waste, fly ash, or bottom ash could be viable solutions to reducing the cost of construction, which is the goal of this thesis. Targon et al. presented inexpensive additives that improve moisture-resistance and strength in concrete.

The natural pozzolan addition to cement decreases moisture permeability, increases chemical resistance, and improves properties of high-strength concrete. Using natural pozzolan also prolongs setting time, which allows proper consolidation. However, concrete mixes with 35% natural pozzolan or more reduces workability. The colemanite ore waste increases setting time, and increases compressive and bending strength. Coal fly ash in concrete reduces expansion, reduces heat generation, and increases durability. Finally, coal bottom ash acts as an inexpensive substitute for sand in concrete and may increase strength in concrete.

Testing results show that mixes with a combination of natural pozzolan+fly ash or natural pozzolan+bottom ash have lower early compressive strength and gradually gain their strength within 90 days. At late curing ages, natural pozzolan and colemanite ore waste combinations show improved concrete strength.

4.1.3 Properties of some cement stabilized compressed earth blocks and mortars

Walker and Stace (1997) investigated manually compressed soil blocks made of soils stabilized with 5% and 10% cement formed from mixing dark-red residual **kaolinite** clay soil with well-graded sand. Kaolinite clay soil is a soft white clay mineral that has a low shrink-swell capacity. In preparation, they air-dried the sand and clay soil, pulverized the clay clumps with a vibrating compactor, and passed the sand and soil through sieves.

They tested these blocks for saturated compressive strength, drying shrinkage, wetting/drying durability, and water absorption.

The blocks were immersed in water for 24 hours prior to saturated compressive strength testing. Results show that saturated compressive strength decreased with increasing clay content. Clay, an absorbent mineral, weakens the bond between the cement and the soil matrix; weak bonds allow pockets of unstabilized soil to form during wet mixing.

ASTM D559 wetting/drying durability tests show that increased clay content also increases dry shrinkage. The blocks were subjected to twelve 48-hour cycles with 6 hours of water immersion and 42 hours of oven drying at 70° Celsius (158° Fahrenheit). If the total reduction in dry mass after 12 cycles is less than 10%, the durability performance is considered satisfactory for general construction.

Results show that the blocks improved in compression and durability with increased cement content and clay content less than 20%.

4.2 Lime literature

Lime is an ancient building material that has been used around the world; the earliest documented use was 4000 BC, when it was discovered that combining burnt limestone with water produced a material that hardened with age. Hydrated lime, a common and less expensive substitute for cement, by pozzolanic action becomes a binding agent that increases durability and strength in adobe.

The lime literature in this thesis is categorized into two sections: 1) Tests performed on lime stabilized adobe and 2) Literature on lime characteristics.

4.2.1 Tests performed on lime stabilized adobe

Various studies have been conducted to evaluate different stabilizers. The following sections 4.2.1.1 through 4.2.1.4 describe lime stabilized adobe tests and conclusions drawn by researchers listed below.

4.2.1.1. *Compressed earth block: achieving building code requirements with lime stabilization,* by Godbey and Thomson (2009)

4.2.1.2. *Microstructure and physical properties of lime-clayey adobe bricks,* by Millogo et al. (2008)

4.2.1.3. *Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure,* by Guettala et al. (2006)

4.2.1.4. *Chemical resistance of pozzolanic plaster for earthen walls,* by Degirmenci and Baradan (2005).

These articles were found beneficial to this thesis, so a summary of each article is provided.

4.2.1.1 Compressed earth block: achieving building code requirements with lime stabilization

Godbey and Thomson (2009) tested lime-stabilized compressed earth blocks (CEB) in laboratory conditions to determine how well lime-stabilized native soils perform as a CEB. Lime-stabilized CEB is a common construction material because lime has proven to be durable especially in the presence of liquid water, and lime’s alkalinity discourages infestation by pests.

Godbey and Thomson began with oven-drying the soil at 824°F to burn away organic matter. The organic matter in the site soil was not burned away in this thesis. For this reason, the bricks made in this thesis performed poorly in the strength and durability tests. For future reference, soil should be taken from deeper than four inches from the surface to minimize the amount of organic material in adobe bricks. Godbey and Thomson's research is relevant to this investigation because it serves as a guide for lime proportions, brick production methods, and testing methods.

CEBs were made with clay and 0%, 1%, 3%, 5%, 7%, and 10% lime measured by volume, and they were tested in dry compression, wet compression, modulus of rupture, water absorption, and moisture content. The lime and native clay soil were thoroughly mixed by hand and the moisture content was gauged with the "ball and drop" test method. The mix has the optimum moisture content when it can be rolled into a two-inch diameter ball, and when dropped onto a hard surface, it forms a pyramidal shaped pile. The test results show that 7% is the optimum lime addition to the CEB because it has the highest dry and wet compressive strengths, lowest absorption, and second highest modulus of rupture. These results indicate that proper carbonation occurred between the native soil and added lime.

Godbey and Thomson's conclusions indicate that the lime-stabilized bricks in this thesis performed poorly because organic material was not removed from the soil and the carbonate in the native soil likely was not adequate for proper carbonation.

4.2.1.2 Microstructure and physical properties of lime-clayey adobe bricks

Millogo et al. (2008) investigated lime's effect on the microstructure properties of lime-clayey adobe bricks throughout the lime's curing process using X-ray diffraction, infrared spectroscopy, differential thermal analysis, scanning electron microscopy, and energy dispersive spectrometry.

Dried native soil, made up of particles smaller than 0.3 mm in diameter, were mixed with proportions of lime up to 12%. These mixes were manually pressed into 4cm x 4cm x 16 cm moulds and left for 30 days to set.

Adding hydrated lime up to 10% enhances the compressive and bending strengths and decreases water absorption of adobe bricks; the combination of lime and quartz-rich clayey soil produces calcium silicate hydrate (CSH) which is the compound that contributes to durability and strength of the lime-stabilized adobe bricks. The CSH contributes the cementitious character of the stabilized adobe bricks. According to Millogo et al.'s test results, adding more than 10% lime in the adobe mix decreases the performance of the lime-stabilized adobe. Excess lime reduces the production of CSH but increases the formation of calcite and portlandite. Calcite and portlandite reduce mechanical resistance, increase porosity, and increase water absorption.

To increase the strength and compaction of lime-stabilized adobe, decrease the grain size of raw materials and increase the duration of hydration. The binding properties of lime are produced by the reaction between lime and fine grains of quartz, so allowing more time for this reaction to occur produces stronger adobe. According to Millogo et al., lime performance is enhanced with quartz-rich clayey soil.

The lime stabilized brick testing results in this thesis confirm that lime-stabilized adobe bricks are optimal when made with soil particle size less than 0.3 mm in diameter; the 7% lime with clay bricks in this thesis had greater strength and durability than the lime bricks mixed with sand.

4.2.1.3 Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure

Guettala et al. (2006) tested stabilized adobe bricks, compacted to 15 MPa (2175 psi), under laboratory and real climatic conditions over four years. The bricks were tested in compressive strength in wet and dry states, capillary and total absorption, wetting and drying, freezing-thawing, and spraying (water jet) in laboratory conditions. The capillary absorption test simulates the bricks' reaction when flooded by water; wetting and drying cycles as well as the freezing-thawing simulate the bricks' durability throughout changing seasons; the water jet test simulates the rainy conditions. The soil used for the stabilized bricks was 64% sand, 18% silt and 18% clay, measured by volume. The mix proportions used are listed:

- 5% cement, 8% cement, 8% lime, 12% lime
- 5% cement +3% lime, and 8% cement+4% lime
- 5% cement+50% resin, and 8% cement+50% resin

Guettala et al. found that the cement + resin mixes had the best strength and durability performance but are the least economical. The mix with the second best performance was the cement only, followed by the cement + lime mixes. The authors found a strong correlation between the performance of the brick mixes tested in laboratory and real climatic conditions even though the laboratory conditions were more severe than the real climatic conditions.

Dry compression results from Guettala et al.'s research and the research done in this thesis (Chen) are compared with code standards in Figure JJ below.

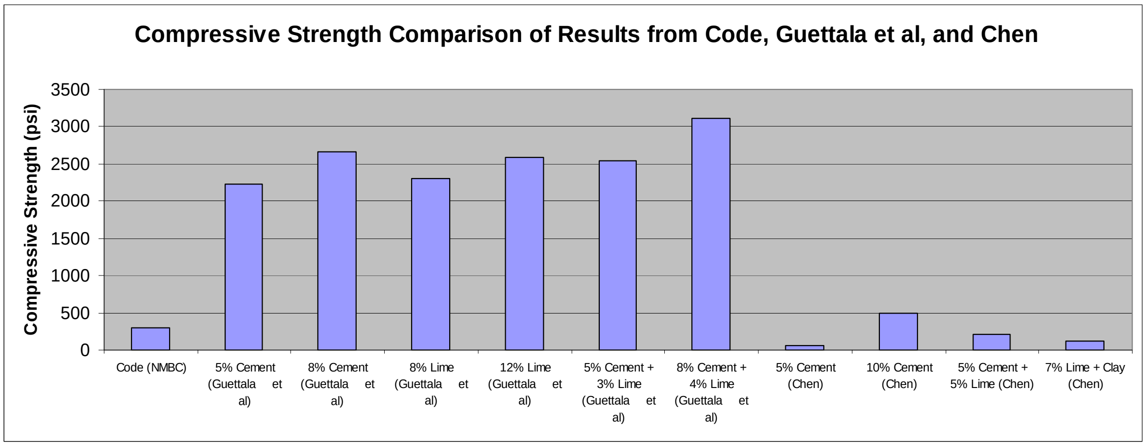

Figure JJ: Compressive strength comparison of code, Guettala et al., and Chen

Guettala et al. recommend using bricks stabilized with 5% cement because the 5% cement bricks had acceptable strength and durability performance and are economical. Compared to cement, lime is more economical but does not perform as well in strength. However, Figure JJ shows that although the 8% lime brick has less compressive strength compared to the cement and cement+lime bricks, the 8% lime brick compressive strength still far exceeds the code limit.

4.2.1.4 Chemical resistance of pozzolanic plaster for earthen walls

Degirmenci and Baradan (2005) mixed fly ash, powdered brick, hydrated lime and water to develop a pozzolanic plaster for historic earthen wall conservation.

Pozzolans are available in rural East Africa, and they are inexpensive supplements to cement. Pozzolans serve to increase durability and strength in adobe.

Degirmenci and Baradan's pozzolanic plaster serves to increase chemical resistance against sulfate, salt, and acid attack. This article shows that lime is an active ingredient that protects earthen walls from the atmosphere's acid and salt attack, which occurs in Tanzania.

The authors used 2000 and 5000 parts per million of sodium sulfate and ammonium nitrate solutions to test earthen walls against sulfate and salt. Testing results show that using fly ash in pozzolanic plaster provides satisfactory resistance against aggressive chemicals such as sulfate, salts, and acids. This plaster is suitable for earthen wall preservation.

Fly ash is a pozzolanic material and it reacts with lime to form a cementitious component that improves strength and hardness of plaster mixtures. Fly ash also reduces shrinkage. Lime also gives good water retention qualities in soil, which will help maintain fluidity.

The fly ash to powdered brick ratio of 1.5 was selected as a suitable type of pozzolanic plaster. It had compressive strength of 7.04 MPa (1021.1 psi) at 28 days, which exceeds the Turkish Standards of 1.0 MPa (145.0 psi).

After eight weeks of immersion in 2000 and 5000 parts per million sodium sulfate and ammonium nitrate solutions, the pozzolanic plaster specimens had no disintegration or weight loss, but there was weight increase.

Tests have shown that fly ash in concrete improves resistance to sulfate attack. High percentages of SiO_2 (quartz) in fly ash increase the sulfate resistance of pozzolanic plaster mixtures. The durability also depends on the CaO (lime) contents in fly ash. Fly ash with low CaO and high SiO_2 is expected to be more durable than the earthen building materials. Degirmenci and Baradan conclude that pozzolanic plaster mixtures are more durable than the conventional cement-lime plaster when subject to 10% concentration of sulfuric acid solution.

4.2.2 Literature on lime characteristics

This portion of the literature review investigates lime's influence when combined with soil. This analysis presents the best environment for lime's optimal performance, which is crucial for this project. Sections 4.2.2.1 through 4.2.2.7 are summaries of articles beneficial to this thesis, as listed below:

4.2.2.1 *What is lime?* by Taylor (1999)

4.2.2.2 *Lime: the basics*, by Taylor (2000)

4.2.2.3 *The technology and use of hydraulic lime,* by Ashurst (1997)

4.2.2.4 *Modeling lime mortar carbonation*, by Balen and Gemert (1994)

4.2.2.5 *Lime mortars and renders: the relative merits of adding cement*, by O'Hare (1995)

4.2.2.6 *Soil acidity and liming*, by Bates (1991)

4.2.2.7 *Slaking of lime,* by Holmberg (2001)

4.2.2.8 *Lime Production from Land-Based Fossil Corals,* by WWF (2005)

4.2.2.1 What is lime?

Taylor (1999) explained that lime is made from burning relatively pure limestone ($CaCO_3$), thus producing calcium oxide (quicklime, CaO). Lime putty, or calcium hydroxide ($Ca(OH)_2$), is produced when calcium oxide is combined or "slaked" in water. Calcium hydroxide carbonates by reacting with the carbon dioxide in the atmosphere, thus reverting back to calcium carbonate. Calcium hydroxide can be stored under water to prevent premature carbonation.

Dry-hydrated lime is hydrated with a precise amount of water to produce a dry powder. The powder is stored in paper sacks where about 16% may revert to calcium carbonate before it is used. Because of this tendency, people prefer lime putty to dry-hydrated lime.

4.2.2.2 Lime: the basics

Taylor (2000) investigated lime, which is commonly categorized into non-hydraulic and hydraulic lime. Non-hydraulic lime is burnt limestone without clay present in the original limestone. Non-hydraulic lime hardens by reacting with carbon dioxide which is present in rainwater and the atmosphere.

Lime putty, a common form of non-hydraulic lime, is set in excess water and continues to mature for months. Lime putty is used for plaster and conservation work. Dry-slaked, another form of non-hydraulic lime, can be used immediately. Bag lime, also known as dry-hydrated lime, is considered inferior to lime putty because it quickly reacts with carbon dioxide but is popular to use because it is easily transported as a bagged powder.

Hydraulic lime is made from limestone which contains particles of clay. After burning, the lime is set to react with water. The limestone containing less than 12% of clay is called **feebly hydraulic lime**; it is relatively weak, permeable, and porous. Higher proportions of clay result in stronger and less permeable mixes. Hydraulic lime reacts with water so it is commonly transported as a powder.

Pozzolanic additives to non-hydraulic lime include brick dust, fired china clay, ash, and pumice. These additives make non-hydraulic lime perform as hydraulic lime. Compared to a standard 1:3 non-hydraulic lime: sand mix, 1:3:9 and 1:3:12 hydraulic lime: non-hydraulic lime: sand performs poorly.

4.2.2.3 The technology and use of hydraulic lime

Ashurst (1997) described the properties of hydraulic lime is separated into four groups: non-hydraulic lime, feebly hydraulic lime, moderately hydraulic lime, and eminently hydraulic lime. Advantages of lime are workability, low shrinkage, salt and frost resistance, adequate compressive and good flexural strengths.

4.2.2.4 Modeling lime mortar carbonation

Balen and Gemert (1994) researched the carbonation reaction that occurs when lime reacts with the carbon dioxide and water in the atmosphere. The carbon dioxide and lime reaction rate decreases with increasing temperature and the optimum carbonation speed occurs at 20° C (68° F). Also, the rate of carbonation decreases with the presence of moisture because the diffusion of carbon dioxide in water is slower than in air.

Balen and Gemert's research shows the importance of monitoring the carbonation climate of lime-stabilized bricks. Relative humidity, wind speed, rain water, and temperature are climatic factors that affect the rate of carbonation. The optimum carbonation climate has low relative humidity, high wind velocity, and high temperature.

4.2.2.5 Lime mortars and renders: the relative merits of adding cement

O'Hare (1995) describes advantages and disadvantages to mixing cement and lime in mortars. To increase the carbonation rate of non hydraulic lime, people add hydraulic limes, cements or pozzolans, which is called **gauging**. An advantage to gauging is that the surface of the mix hardens quickly, which decreases the size and number of cracks; a hard surface protects the lime-stabilized block from moisture before the carbonation has completed.

A disadvantage to gauging is that segregation is likely to occur since the surface of the block sets much faster than the interior of the block. However, a sufficient proportion of cement decreases the likelihood of segregation. O'Hare recommends using 1:1:6 rather than a 1:2:9 cement, lime, sand mix because a mix containing 50% cement binder is unlikely to segregate. This recommendation confirms that the 5% cement+5% lime stabilized adobe brick mix in this thesis contains acceptable binding proportions.

4.2.2.6 Soil acidity and liming

Bates (1991) explains that acidic sandy soils are low in neutralizing elements such as magnesium and calcium. Plants tend to absorb calcium and magnesium which leaves hydrogen and aluminum ions more prevalent in the soil, leading to acidic soil. Acid rain, which is common in Tanzania, also contributes to the acidity of soil.

The pH of soil is important to this analysis because soil with a high concentration of calcium enhances the performance of lime-stabilized adobe bricks. One way to identify whether calcium is prevalent in soil is to obtain the pH of the soil. A high pH indicates alkaline soil, which usually indicates the presence of calcium.

4.2.2.7 Slaking of lime

Holmberg (2001) explains that quicklime is produced when limestone ($CaCO_3$) is heated above 900°C (1562°F) at which point the limestone decomposes to carbon dioxide (CO_2) and quicklime (CaO).

Homberg tested lime from Sweden, China, and Poland. The lowest density of lime or the highest pore volume lime is most reactive. Adding calcium chloride ($CaCl_2$) also increases reactivity.

4.2.2.8 Lime Production from Land-Based Fossil Corals

WWF For a Living Planet (2005) researched lime production and its effect on Eastern African marine ecology. According to WWF (2005), lime is an inexpensive and popular substitute for cement. However, live coral mining is often used as a means for lime production. To create lime, coral is collected from the Indian Ocean shores and then burned. Because lime has become increasingly popular for construction in East Africa, reef and forest degradation is common along the coast, especially in Tanzania. The impacts of live coral mining include the reduction of shelter and refuge for reef fish and marine life, increased erosion of shoreline, and reduced local fish populations.

Fossilized corals, which are found along the coast of East Africa, are an alternative to live coral mining for lime production. Fossilized corals are abundant along the East African Coast and they produce high quality limes for structures (WWF 2005).

In Tanzania, the availability and affordability of construction materials drive the construction process. Concrete is not a common construction material used in rural East Africa because cement is costly and formwork is both costly and scarce. Instead, lime-stabilized adobe bricks are used because lime is an inexpensive alternative to cement, and adobe bricks can be made with a manual press so formwork is not required.

4.3 Literature of other adobe stabilizing agents

The sections 4.3.1 through 4.3.3 introduce natural and chemical additives other than cement and lime that improve the durability of adobe. The articles and authors are:

4.3.1 *Improving the moisture resistance of adobe structures*, by Heredia Zovani et al. (1988)

4.3.2 *High strength concrete containing natural pozzolan and silica fume*, by Shannag (2000)

4.3.3 *The using of waste phosphogypsum and natural gypsum in adobe stabilization,* by Degirmenci (2008).

4.3.1 Improving the moisture resistance of adobe structures

Heredia Zavoni et al. (1988) made and tested mud plasters to improve moisture resistance in adobe. Heredia Zovani et al.'s test methods and results are used as a reference in this analysis. Their plasters had the following mixtures:

- Plain Soil
- Soil with Banana Stabilizer Solution
- Soil with Cactus Stabilizer Solution
- Soil with 2% Asphalt Emulsion
- Soil with 4% Asphalt Emulsion

Each plaster was subject to wetting and drying cycles of the water jet test. Test results show that only the asphalt emulsion stabilizers had light visual damage; the remaining mixes were severely damaged. This stimulated rain test showed that banana and cactus stabilizers are not sufficient in resisting moisture but do aid in reducing crack sizes. The banana and cactus stabilizers slow down the rate moisture evaporation thus decreasing the number of cracks.

Heredia Zovani et al. made clay adobe wall surfaces with different proportions of sand and straw to investigate sand and straw's effect on reducing cracks. After the clay adobe walls dried, the fewest cracks occurred in the mix with 50% coarse sand and 2% straw, which also had adequate workability. Heredia Zovani et al. found that sand reduces crack widths and straw aids in adhering the adobe plaster to the adobe bricks.

Reducing the number and size of cracks increases adobe's resistance against moisture permeation. An additional way to reduce moisture permeation is smoothing the stucco surface with a flat stone before the adobe block has cured. The smooth surface once hardened causes water drops to slide off instead of being absorbed into the wall. Creating a smooth surface on the walls is an easy and effective way of providing moisture-resistance in adobe structural elements.

4.3.2 High strength concrete containing natural pozzolan and silica fume

M.J. Shannag (2000) researched how combinations of natural pozzolan and silica fume produced workable high to very high strength mortars and concretes. The mixtures were tested for workability, density, compressive strength, splitting tensile strength, and modulus of elasticity.

Test results show that 15% silica fume combined with 15% pozzolan had optimal workability and produced the highest strength increase compared to silica fume or pozzolan alone. This strength increase occurred due to improved interlock between binder and aggregate. Shannag's research was used as guide for the testing methods in this thesis.

4.3.3 The using of waste phosphogypsum and natural gypsum in adobe stabilization.

Degirmenci (2008) investigated **waste phosphogypsum** (PG) and natural gypsum as adobe stabilizers alternative to cement, lime, and asphalt. PG is a by-product of industrial waste that has been recycled and used in small amounts in soil and road stabilization. However, the remainder of the PG has been deposited in open areas or dumped into the sea. The average production of PG is three million tons a year in Turkey.

PG contains naturally-occurring radioactivity, so the Environmental Protection Agency has set a safety limit. Studies have indicated that using PG as a by-product is better for the environment than depositing it in open areas or into the sea.

The soil used in these stabilized adobe bricks have grain size distribution of 1% gravel, 18% sand, and 81% fines. These stabilized adobes were tested in compression, flexure, softening in water, and dry shrinkage.

The stabilizers in each adobe brick varied from 0% to 25%. Compressive and flexural strength increased with increased addition (10% or more) of both types of gypsums. The highest compressive strength and the lowest shrink rate were achieved with 25% addition of both types of gypsums. Degirmenci's research shows that waste phosphogypsum and natural gypsum are viable alternatives to cement, lime, and asphalt in stabilizing adobe.

4.4 Additional stabilized adobe sources

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4.5 Adobe literature

Adobe has favorable characteristics in arid climates but lacks integrity in moisture or high seismic regions. This thesis aimed to improve living conditions in rural East Africa by suggesting moisture-resistant construction materials. Another factor to improving living conditions is building structures that can stay intact during seismic events. Sections 4.5.1 and 4.5.2 describe researchers' methods in stabilizing adobe in seismic regions, as listed below.

4.5.1 *Seismic stabilization of historic adobe structures*, by Tolles et al. (2000)

4.5.2 *Earthquake-resistant construction of adobe buildings: a tutorial*, by Blondet et al. (2003).

4.5.1 Seismic stabilization of historic adobe structures

Tolles et al. (2000) described adobe as the ultimate recyclable and renewable resource since it is a raw material taken from the earth and it eventually returns to the earth. Adobe has favorable features for construction in arid regions: it provides effective thermal insulation, the clayey soil is commonly available, the skill and experience required for building adobe structures is minimal, and building construction does not require the use of scarce fuel.

Adobe buildings are considered the weakest type of structure in the unreinforced masonry category since adobe buildings have been devastated in areas of high seismicity. Each significant earthquake destroys or degrades the authenticity of historic structures. Also, brittle behavior of unreinforced materials is extremely difficult to predict after cracks have occurred. The seismic behavior of adobe buildings after cracking is dominated by the interactions of large, cracked sections of walls that collide against each other during an earthquake.

California has been retrofitting to stabilize historic structures by preventing the overturning of walls during a seismic event. In the process of retrofitting historic structures, improvements to a structure's seismic safety can lead to damage to the historic architectural or decorative features. Tolles et al. developed technical procedures for improving the seismic performance of historic adobe structures such as providing life safety and maintaining architectural, historic, and cultural conservation values.

Unreinforced adobe has poor seismic performance because the material has low ductility and low strength. Even after a typical adobe wall has cracked and the tensile strength is lost, the wall can continue to carry vertical loads as long as it remains upright and stable. The thickness of typical historic adobe walls makes the walls difficult to destabilize even when severely cracked. Overturning of adobe walls during an earthquake is not a concern since they have small height to thickness ratios. They are inherently stable and have great potential for absorbing energy.

One way to improve structural strength during severe seismic activity is to replace the center of an adobe wall with reinforced concrete. However, compatibility problems between concrete and adobe may occur which leads to more effort in retrofit.

Another way to provide structural integrity is to place reinforced concrete bond beams at the top of walls below the roof, which provide lateral support and continuity. However, installation usually requires removing the roof system. The stiffness of the bond beam may be two to three times greater than the stiffness of the walls so the adobe walls may pull away from bond beams during an earthquake.

4.5.2 Earthquake-resistant construction of adobe buildings: a tutorial. EERI/IAEE world housing encyclopedia

Blondet et al. (2003) explained that adobe construction is widely used in low-income rural areas around the world. Earthquake resistance, like moisture-resistance, is important for improving living conditions in rural areas. Since adobe will continue to be used as a construction material, improving adobe's performance in earthquakes is important in high seismic areas. The key factors to improving adobe's earthquake resistance are improving quality of construction, designing a robust layout, and installing seismic reinforcement in adobe.

The quality of construction also affects the performance of adobe structures. Because adobe construction is often used by unskilled laborers, the quality of bricks varies greatly.

Blondet et al. recommend performing a preliminary dry strength test to examine the integrity of the clay to be used in adobe construction. Mix the selected soil with water and roll the mix into a two-inch ball. After 24 hours, press the ball between your thumb and the side of your index finger. If the ball remains intact, the adobe mix is sufficient for adobe construction. Another field test is the roll test. Roll the mud until it is 10 cm in length. If the soil can maintain a 10 cm length without breaking, the soil is adequate for adobe construction. If the unbroken roll extends longer than 15 cm, add coarse sand to the mix.

Blondet et al. emphasize slightly wetting the adobe bricks before laying them into the wall. Clay is an absorbent material so if the adobe is not slightly wet during building, it will naturally absorb the moisture from the mortar, thus preventing the mortar from properly bonding the adobe bricks.

Blondet et al. recommend storing the clay that will be used for adobe construction for one or two days before using. Storing the clay allows for better distribution of water with clay particles, thus improving cohesive properties of clay.

Blondet et al. also provide adobe wall specifications. Adobe wall height should be limited to eight times the wall thickness. The unsupported length of walls should not be ten times greater than the wall thickness. The wall openings for doors and windows should not be greater than a third of the total wall length. Also, provide at least 1.2 meters of pier width between openings.

Blondet et al. recommend providing horizontal and vertical reinforcement in the adobe walls. Reinforcement can be any ductile material including bamboo, rope, timber, chicken wire, barbed wire, or steel bars. Vertical reinforcement connects the wall to the foundation and horizontal reinforcement transfers out-of-plane forces into supporting walls which can take that force in-plane. Horizontal reinforcement also restrains shear stresses and protects the walls from vertical cracking.

Blondet et al. found that typical earthquake failure modes are cracking and disintegration of walls, separation of walls at corners, and separation of roof from walls which ultimately leads to collapse.

4.6 Rammed Earth

Apart from adobe bricks, earth is also commonly used in rammed earth. Rammed earth could be considered an advanced form of compressed adobe bricks. The research done on rammed earth relating soil particle size and moisture resistance can be applied to adobe brick construction. Sections 4.6.1 through 4.6.7 summarizes articles about rammed earth characteristics, as listed below:

4.6.1 *Rammed earth sample production: context, recommendations and consistency*, by Hall and Djerbib (2003)

4.6.2 *Moisture ingress in rammed earth: Part 1 – the effect of soil particle-size distribution on the rate of capillary action*, by Hall and Djerbib (2003)

4.6.3 *Moisture ingress in rammed earth: Part 2 – the effect of soil particle-size distribution on the absorption of static pressure-driven water*, by Hall and Djerbib (2006)

4.6.4 *Compressive strength characteristics of cement stabilized rammed earth walls*, by Jayasinghe and Kamaladasa (2007)

4.6.5 *Use of bottom ash and fly ash in rammed earth construction*, by Fine and Porter (1999)

4.6.6 *Structural capacity of rammed earth in compression*, by Maniatidis and Walker (2008)

4.6.7 *Soil property criteria for rammed earth*, by Burroughs (2008)

4.6.1 Rammed earth sample production: context, recommendations and consistency

Hall and Djerbib (2003) investigated rammed earth, which is a building method that compacts moist soil between formwork to produce a strong and durable wall. Rammed earth has a reputation for sustainability and good thermal and acoustic characteristics.

For soil selection, Hall and Djerbib recommend avoiding topsoil, which usually has a high percentage of organic matter. Because organic matter biodegrades, absorbs water, and is highly compressible, the amount of organic matter should be limited to 1 to 2% of the total mass of the soil. Hall and Djerbib oven-dried the sily clay soil to a constant mass at 105° C to burn away the organic matter. Then the soil was pulverized into a coarse powder.

Achieving the optimum moisture content (OMC) for rammed earth is important. With too little water, the soil cannot achieve the right level of compaction. With too much water, capillary water occupies the soil pore space and reduces the level of compaction. Rammed earth should have OMC between 3 and 5%.

Rammed earth and chemical binder mixes were cured in a sealed curing chamber for 28 days at 20° C with relative humidity of 75%. Samples with high binder proportions had visible shrinkage cracks but were smooth and had a hard surface finish. The high sand content samples were stable with no visible cracking. Hall and Djerbib recommend rammed earth soil mixes with high binder and sand proportions.

4.6.2 Moisture ingress in rammed earth: part 1 – the effect of soil particle-size distribution on the rate of capillary suction

Hall and Djerbib (2003) performed the initial rate of suction (IRS) “wick” test to determine the rate of capillary moisture absorption in unstabilized rammed earth. Rammed earth construction is known to perform well in warm, dry climates, so Hall and Djerbib seek to determine whether rammed earth can be used in temperate damp climates. Dampness, defined to be the excessive moisture content in building elements, permeates into porous construction materials through open channels. Because rammed earth walls are monolithic, the capillary movement of moisture within the walls is problematic.

The IRS test began with weighing a dry specimen and placing the specimen on a shallow tray of clean water kept at 20°C. The specimen absorbed water by capillary action and distributes the water throughout the pore network of the brick. Hall and Djerbib found that the capillary movement of water travels twice as far horizontally than vertically due to the force of gravity. Also, if a temperature gradient exists, the capillary movement will flow toward the area of lower temperature. Hall and Djerbib then weighed the specimen after it absorbed water. The same samples were dried and tested repeatedly. Hall in his previous research observed that no changes occurred in the pore structure of fired clay bricks during repeated tests like these.

Rammed earth generally absorbs less water over a given time span compared to concrete and fired clay bricks. Decreased absorption is due to high density and lower porosity in the rammed earth.

The particle size distribution of soil is critical in determining the moisture absorption rate due to capillary suction. The water penetration into rammed earth alters its properties so that in a repeat test, the IRS decreases. The moisture absorption in rammed earth due to capillary suction increases linearly against the square root of elapse time. This finding allows predictions to be made on the rate and amount of moisture ingress at a given point in time. By modifying the particle-size distribution throughout the material, the rate of capillary moisture ingress in rammed earth can be controlled.

4.6.3 Moisture ingress in rammed earth: part 2 – the effect of soil particle-size distribution on the absorption of static pressure-driven water

Hall and Djerbib (2006) investigated water absorption through the surface of exterior masonry walls. Hall and Djerbib explain that rainfall, condensation, moisture infiltration and absorption all contribute to the deterioration of rammed earth building. Water penetration through the external building envelope causes

- Water staining
- Damaged internal finishes
- Damage caused by cyclic wetting and drying
- Fracturing caused by fatigue loading
- Rotting timbers
- Freeze/thaw damage of saturated masonry
- Decreased thermal performance
- Uncomfortable and unhealthy ambient air conditions inside the affected building
- Damaged electrical installations
- Loss of adhesion between binding agents and aggregates
- Sulfate attack of Portland Cement
- Corrosion of metals.

Water penetrates through the rammed earth building envelope when a force moves water through capillaries and when pressure differences occur between the inside and outside of the building. High air pressure outside the building exists because of the wind pressure exerted on the external face of the walls. According to the laws of thermodynamics, moisture migrates toward areas with least pressure to conserve energy in the system, which causes moisture to be absorbed into the building envelop thus deteriorating the earth material. Moisture permeation is influenced more by pressure differences than by rainwater absorption.

A favorable design of earth wall has an exterior façade that becomes saturated only to a certain depth. Then, little or no water penetrates beyond this wetted region. Instead, any additional water runs off the surface because moisture can no longer be absorbed by the already-saturated wall surface layer. Another theory is the "impervious skin" analogy where the outer layer does not allow water penetration because the façade is lined by materials such as silicone, acrylic, latex, or water glass. This concept is effective as long as the layer does not deteriorate. Any weak zones of the impervious skin result in concentration of moisture penetration, as show in the Figure KK on the next page.

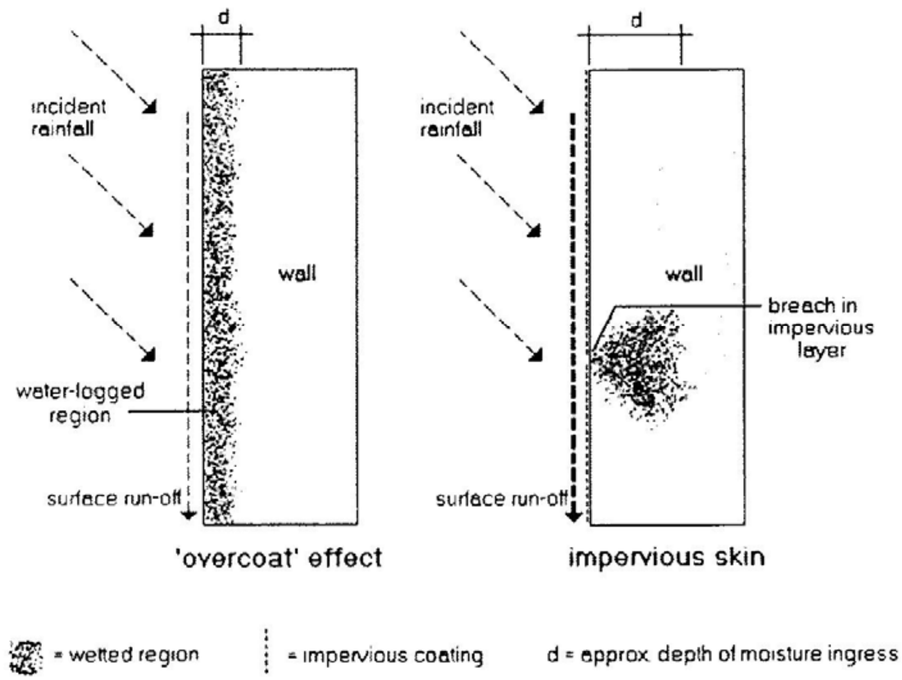

Figure KK: Hall and Djerbib's impervious skin analogy
Source: Hall and Djerbib (2006)

Also, the water that penetrated the skin evaporates thus leaving behind salt crystallization and causing spawling at the surface. Testing results show that the moisture ingress performance is optimal with 6 - 9% cement addition. Failure in unstabilized rammed earth may occur due to loss of cohesion between clay. The authors recommend cement stabilization for rammed earth building applications.

4.6.4 Compressive strength characteristics of cement stabilized rammed earth walls

Jayasinghe and Kamaladasa (2007) investigated cement stabilized rammed earth and its compressive strength. They sought to select suitable soil types for rammed earth construction, determine strength characteristics of cement stabilized rammed earth walls, and suggest desirable practices for rammed earth wall construction. Results indicate that rammed earth may be used for single story houses that extend to two story houses.

Commercial exploitation of clay and river sand has led to environmental problems. Unfilled clay ditches can collect water and become a breeding spot for mosquitoes. Extensive sand mining can lower river beds and allow salt water intrusion inland.

Even with the ecological effects, Jayasinghe and Kamaladasa encourage using locally available soil types because transportation costs decrease and soil is recyclable. This research was conducted using **laterite** soil in Sri Lanka, a reddish soil formed in tropical regions by igneous or metamorphic rock weathering.

Clay and silt particles smaller than 0.06 mm should be less than 30% for optimal rammed earth compressive strength. Soils for rammed earth shall not have particles larger than 38 mm (1.496 inches) in diameter. Tests show that rammed earth wall compressive strength drastically decreases when fine soil content increases above 40%.

Jayasinghe and Kamaldasa found that unstabilized rammed earth yields compressive strength of 1.0-3.0 N/mm^2 (145 psi – 435 psi) and compressive strength multiplies when the earth is stabilized with cement. Laterite soils stabilized with cement have higher compressive strength than clayey soils stabilized with cement, so the local laterite soil was recommended for future construction.

4.6.5 Use of bottom ash and fly ash in rammed-earth construction

Fine and Porter (1999) investigated rammed earth construction that is used in dry regions throughout the United States. Although some soils are naturally adequate for rammed earth construction, additives are frequently used to increase strength and durability in rammed earth walls. For rammed earth construction in North Dakota, Fine and Porter added varying proportions of bottom ash, fly ash, and Portland cement to increase wall strength and durability.

A summary of building codes of earth construction shows that a desirable level of strength is 90 psi for uncured rammed earth and 300 psi for cured rammed earth. These levels served as a guideline for selecting favorable mixes.

Mixes with fly ash or fly ash + cement performed better than soil alone or soil + bottom ash in all strength and durability tests. Scanning electron microscopy showed the level of cementation between particles and did not show any evidence of cementation in the soil + bottom ash sample.

Fly ash and bottom ash is technically feasible and environmentally safe. Testing showed that the North Dakota soil requires cement or cement + fly ash to improve durability.

4.6.6 Structural capacity of rammed earth in compression

Maniatidis and Walker (2008) found that rammed earth construction is generally designed to structural masonry standards, a practice that has not been satisfactorily validated. Maniatidis and Walker investigated large-scale rammed earth walls subject to concentric and eccentric axial compression loading to validate the use of masonry design rules for rammed earth design.

Maniatidis and Walker made unstabilized rammed earth with soil size 20-25 mm and 8-15% clay. After testing the mix in uniaxial compression, the average unconfined compressive strength was 2.46 N/mm^2 with an initial tangent elastic modulus of 160 N/mm^2.

The study found significant variation in material performance between small-scale 100 mm diameter cylinders and full-scale prisms and columns using the same material. The reduced compressive strength and stiffness of the full-scale specimen is due to variation in material grading, which includes aggregates greater than 20mm. With greater aggregate size, the compaction varied throughout the specimen. For small load eccentricities (up to 10%) the 2001 Australian Standards and the New Mexico Building Code provisions provided a good estimate of measured experimental performance.

4.6.7 Soil property criteria for rammed earth

Burroughs (2008) investigated how natural soil properties relate to the performance of rammed earth wall construction. Burroughs stabilized walls with cement, lime, or asphalt, and observed each wall's compressive strength, linear shrinkage, and plasticity index. Burroughs found that favorable soils had stabilization success rates of greater than 80%, linear shrinkage less than 6.0%, and plasticity index less than 15%.

Burroughs also found that fine-grained soils react most favorably with lime, so lime stabilization was just as effective as cement for clayey soils. To enhance cement stabilization, Burroughs recommended using clay soils of low to medium plasticity and low clay content soils such as sands and silty soils. Soils unsuitable with any stabilizer are organic soils, clean gravels and sands, and highly plastic clays.

Samples with 21-35% clay or silt contents were more likely to be successfully stabilized than samples with higher clay or silt contents. Burroughs found that all samples with 30-62% gravel were successfully stabilized and 82% of the samples with 15-30% gravel were successfully stabilized. As for sand content, samples with less than 48% sand were successfully stabilized. Burroughs also found that none of the samples with a liquid limit greater than 57% were successfully stabilized.

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APPENDIX A: Glossary

Adobe: a mixture of sand, silt, and clay mixed with water, which can be used as mortar between stone or adobe brick, or used as a plaster

Augmented adobe: adobe mixed with natural materials such as bamboo, straw, or rice hulls to decrease the size and amount of cracks in adobe

Coal bottom ash: coarse material collected from the bottom of furnaces that burn coal for steam generation

Coal fly ash: fine-grained ash that leaves the furnace when burning pulverized coal

Durability: the lasting and enduring ability to resist wear and decay

Feebly hydraulic lime: lime made from limestone containing less than 12% of clay

Gauging: Adding hydraulic lime, cement, or pozzolans to increase the rate of carbonation in lime-stabilized mixes.

Kaolinite: soft, white clay mineral that has low shrink-swell capacity produced by chemical weathering of aluminum silicate minerals.

Laterite: a red soil found in tropical regions made from igneous or metamorphic rock weathering

Pozzolan: a fine material found on the earth's surface that reacts with calcium hydroxide and alkalies to form cementitious properties. Pozzolans can be volcanic ash, shale, tuff, brick dust, fired china clay, ash, and pumice.

Stabilizers: chemical agents added to adobe to increase durability and strength

Stabilized Adobe: adobe with chemical additives, such as cement and lime, which limits water absorption and increases strength

Sustainability: the use of immediate and cost effective resources; environmental stewardship, social betterment, and economic growth

Waste phosphogypsum: a by-product of industrial waste that has been recycled and used for soil and road stabilization

APPENDIX B: List of Acronyms

ASTM: American Society for Testing and Materials

CEB: Compressed Earth Blocks

MSJC: Masonry Standard Joint Committee

NMBC: New Mexico Building Code